

# **Nondestructive Evaluation Aerospace Composites**

**Dr. Cara Leckey, Elliott Cramer, Daniel Perey**

**Nondestructive Evaluation Sciences Branch**

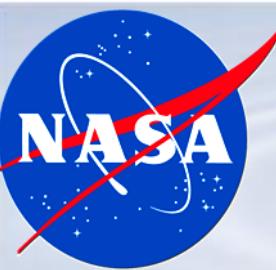
**NASA Langley Research Center**



# Outline

Nondestructive Evaluation Sciences Branch

- National Aeronautics and Space Administration (NASA)
- NESB Overview
- Need for NDE of Composites
- NESB NDE Composites Research
- Conclusion



Nondestructive Evaluation Sciences Branch

# NASA Locations

- NASA
- NESB
- Need for composites NDE
- NESB Research
- Conclusion

14 Major Centers/Facilities

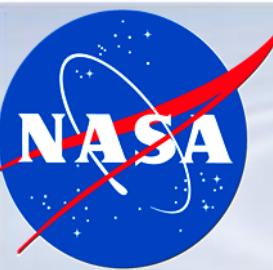
~18,000 Civil Service Employees

~40,000 Contract Employees



## Centers:

- Ames Research Center
- Armstrong Flight Research Center
- Glenn Research Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center
- NASA Headquarters
- Stennis Space Center
- Wallops Flight Facility



# NASA Langley Research Center

Nondestructive Evaluation Sciences Branch

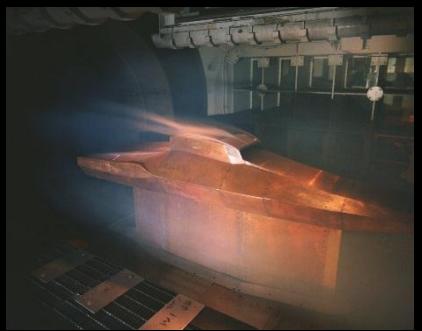


A picture from 1934 that includes Charles Lindbergh, Howard Hughes, Glenn Curtiss and Orville Wright is an indicator of the history of LaRC.



Alan Shepard at Lunar Landing Research Facility  
NASA Langley Research Center  
3/30/1970  
Image # EL-1996-00219

A picture from 1970 of Alan Shepard (1<sup>st</sup> American in space) at LaRC lunar landing facility.



Supersonic  
vehicles



Autonomous vehicles



More efficient vehicles

# Aeronautics Research



Personal Air  
Vehicles



Air traffic



Safer vehicles

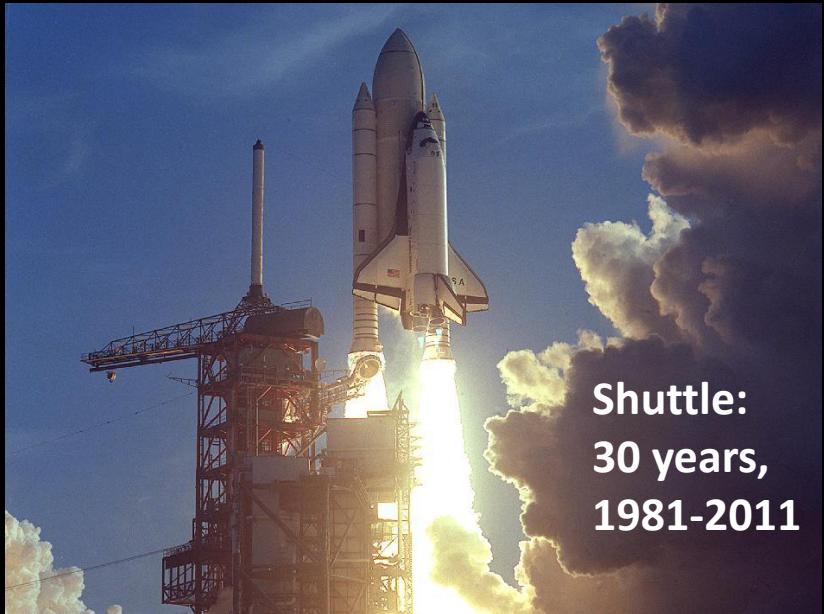


Commercial  
Crew to ISS



Space Launch System (SLS)  
Beyond LEO  
Asteroid, Mars

# Human Exploration



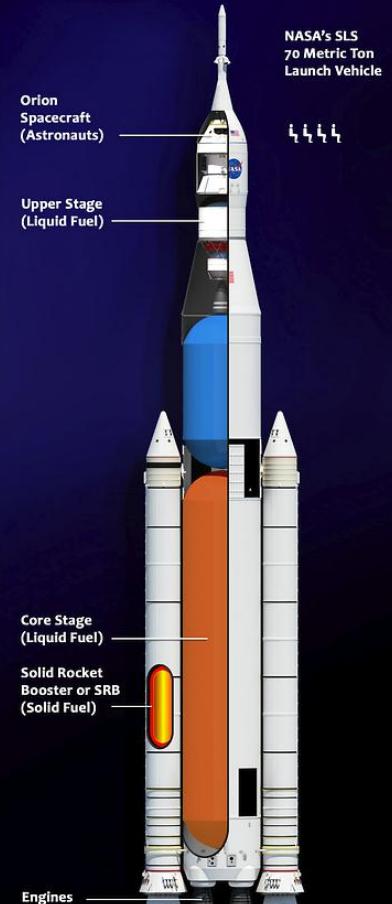
If you wonder how NASA's Space Launch System, or SLS, compares to earlier generations of NASA launch vehicles...



SLS will produce 8% more thrust at launch than the space shuttle and 12% more than the Saturn V.

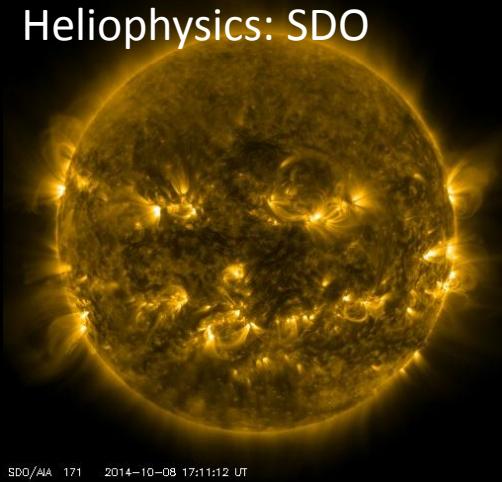


SLS will launch more than three times as much weight into space as the space shuttle.



# Science

Heliophysics: SDO

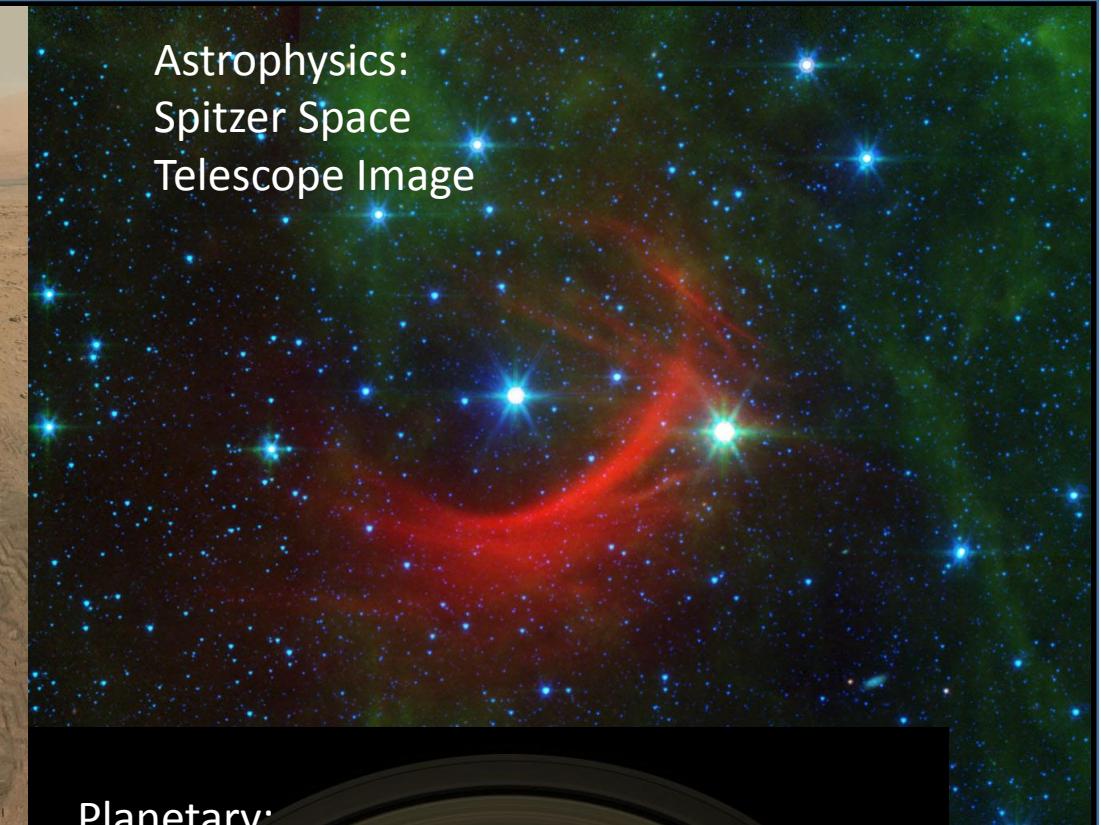


SDO/AIA 171 2014-10-08 17:11:12 UT

Mars Science  
Laboratory:  
Curiosity



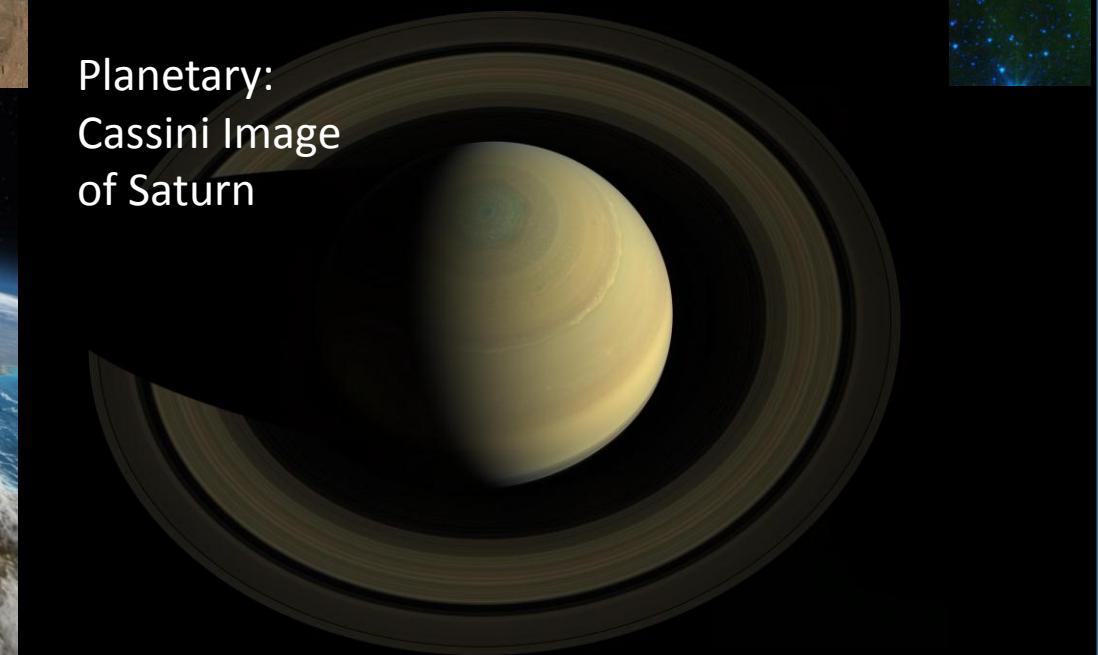
Astrophysics:  
Spitzer Space  
Telescope Image



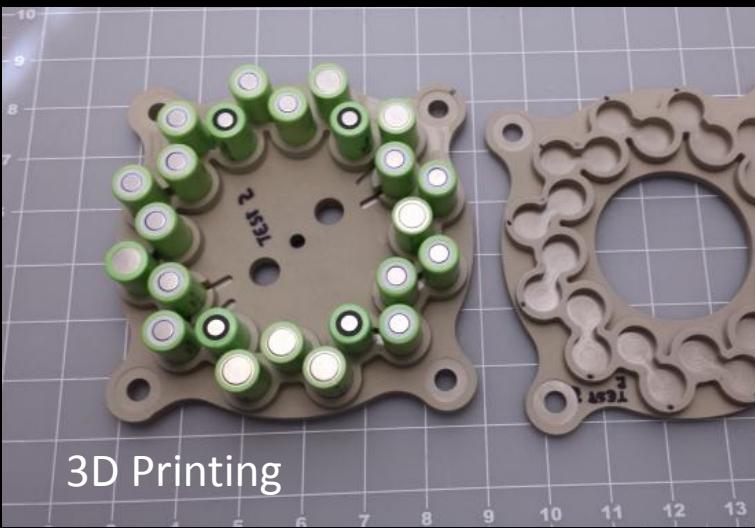
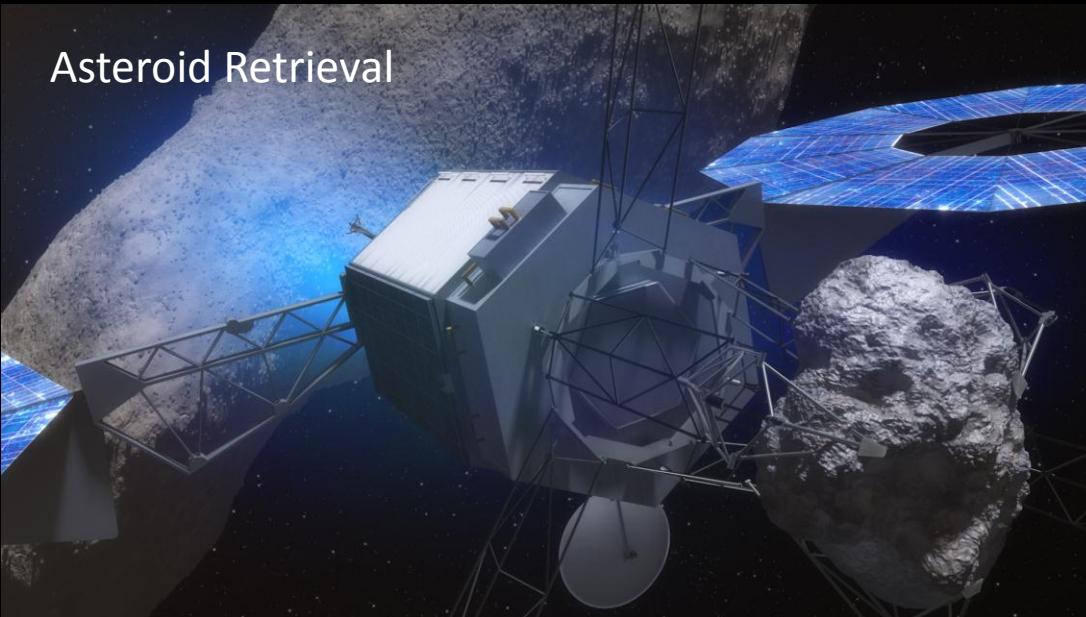
Earth Science:  
Orbiting Carbon Observatory

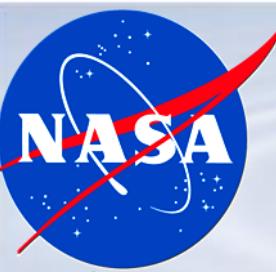


Planetary:  
Cassini Image  
of Saturn



# Space Technology

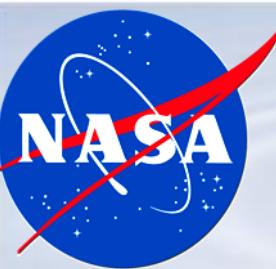




# NESB

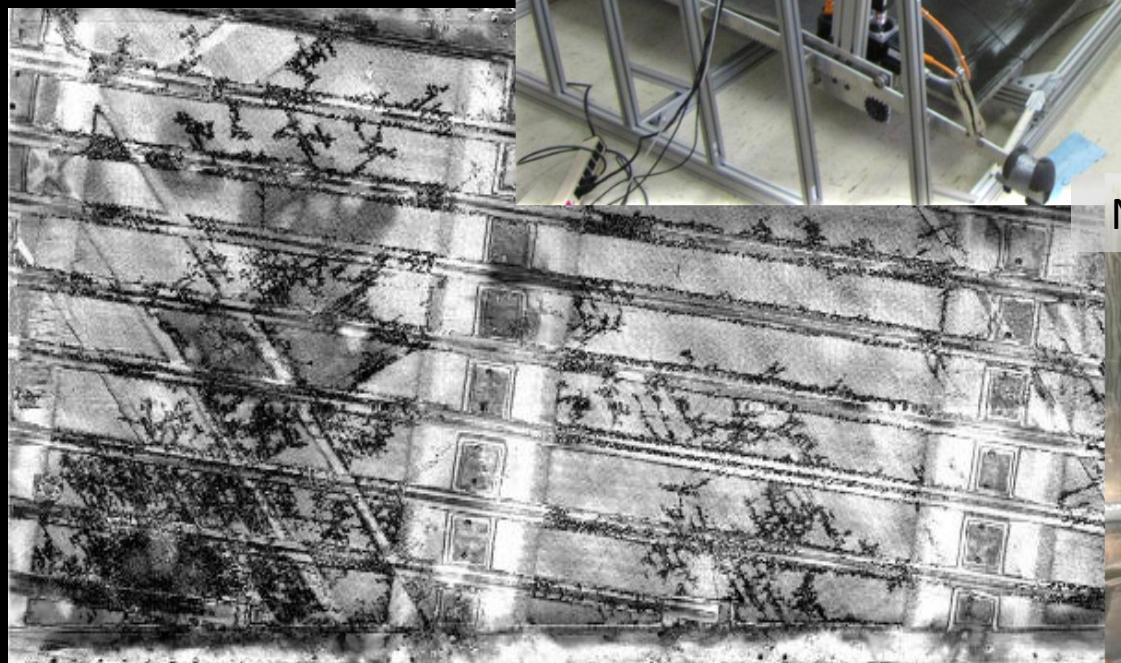
- NASA
- NESB
- Need for composites NDE
- NESB Research
- Conclusion

- Only branch level NDE at NASA
- 1 of 2 NDE research level organizations in the US government
- ~24 Full-Time Personnel
  - 18 Civil Servants
  - 9 Support Contractors
- Extensive Skill Mix
  - 10 PhD's
  - 65% Physicist
  - 15% Electrical Engineers
  - 15% Mechanical Engineers
  - 5% Aerospace Engineers
- NDE Research Laboratory
  - Thermal Imaging
  - Ultrasonic Scanning
  - Phased-Array Ultrasound
  - Electromagnetics
  - Computed X-Ray Tomography
  - Photo & Thermal Elasticity
  - Scanning Electron Microscopy
  - Terahertz Imaging
  - Fiber Optic Sensors Fab.
  - Nano & Mems Sensor Fab
  - Raman Spectroscopy

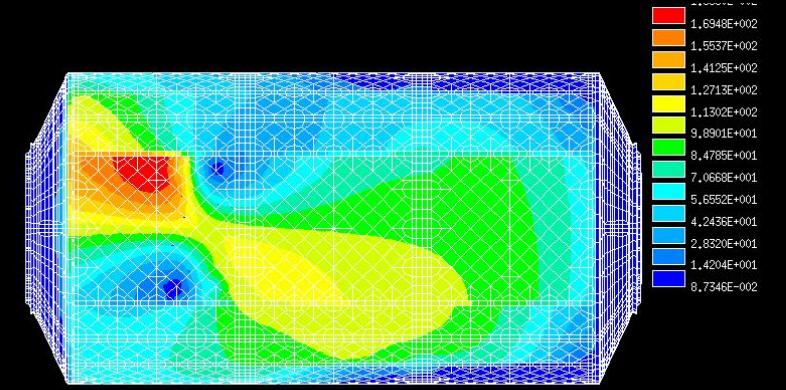
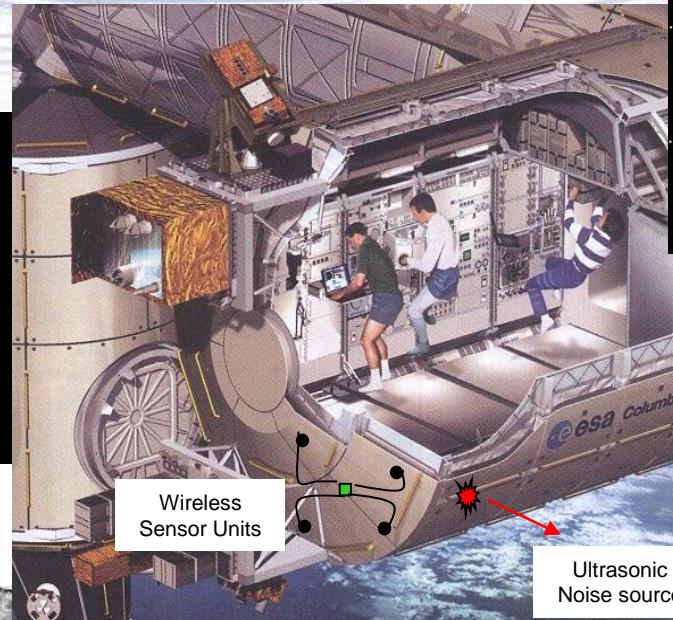


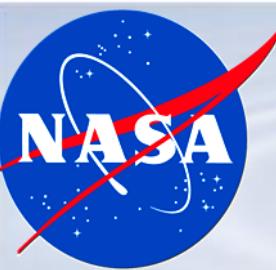
# Ultrasound

Nondestructive Evaluation Sciences Branch



Nonlinear Acoustics

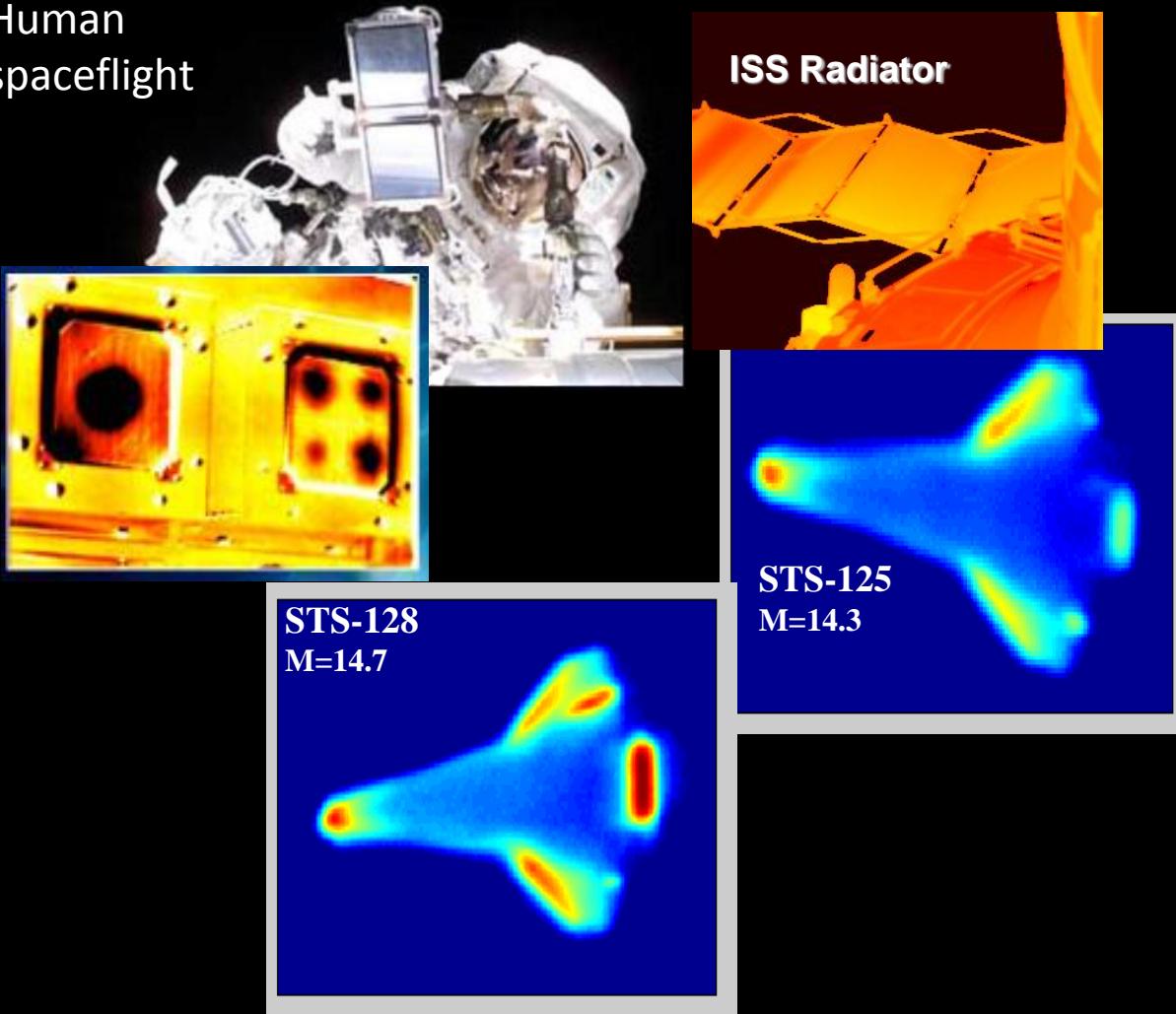




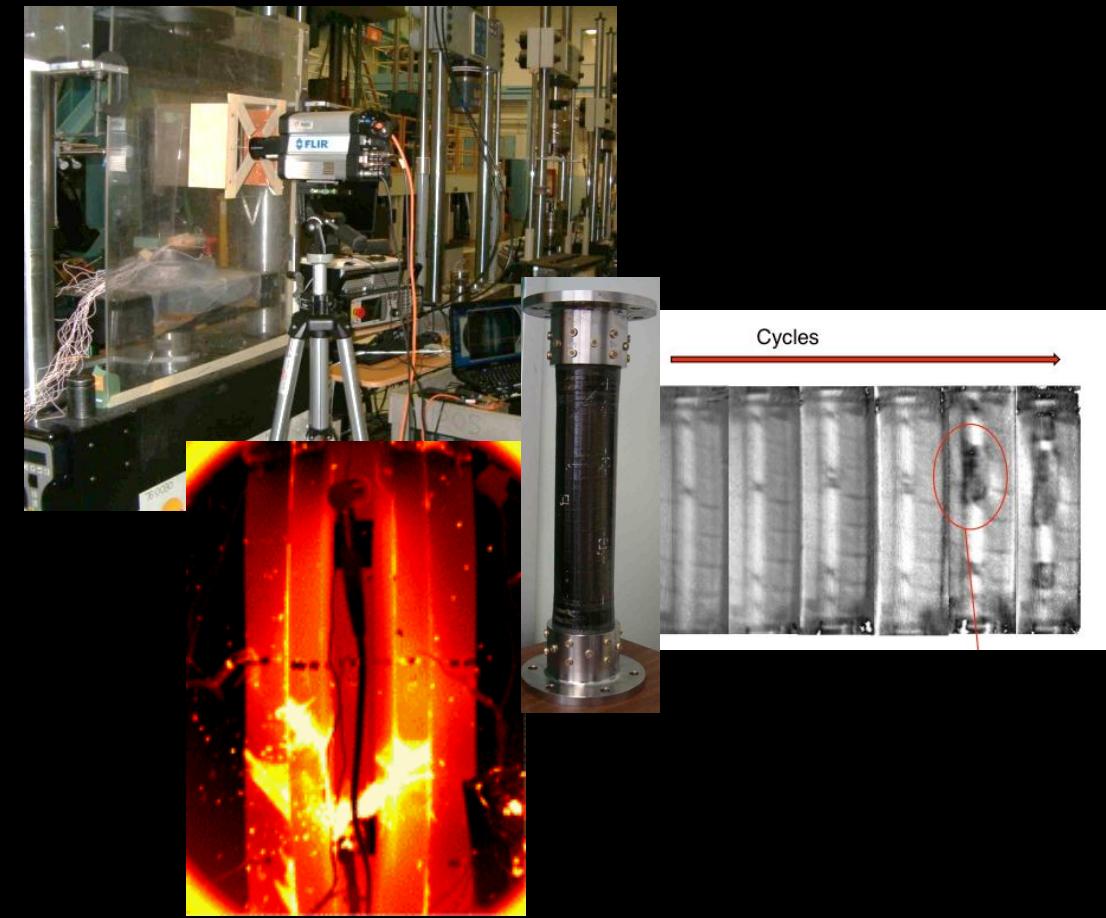
# Thermography

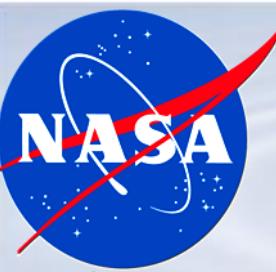
Nondestructive Evaluation Sciences Branch

Human  
spaceflight



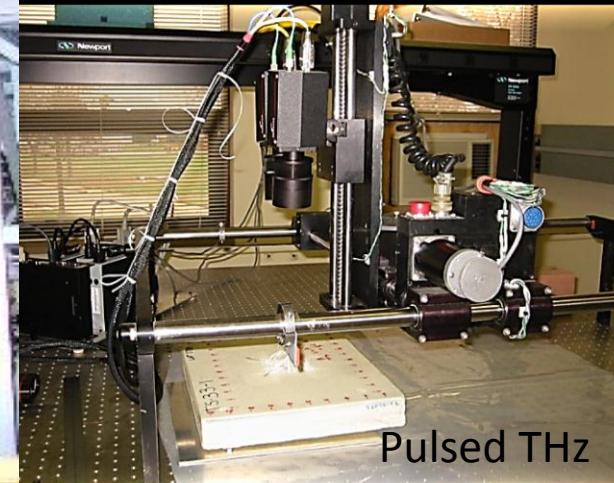
Real time inspection during loading



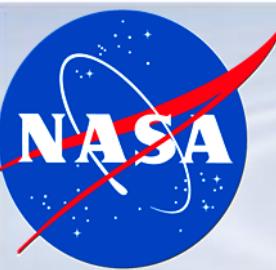


# Terahertz

Nondestructive Evaluation Sciences Branch

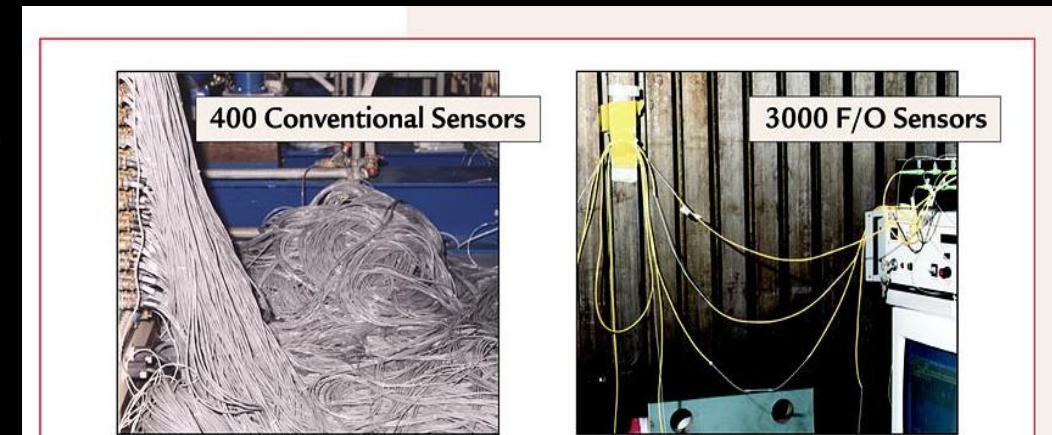
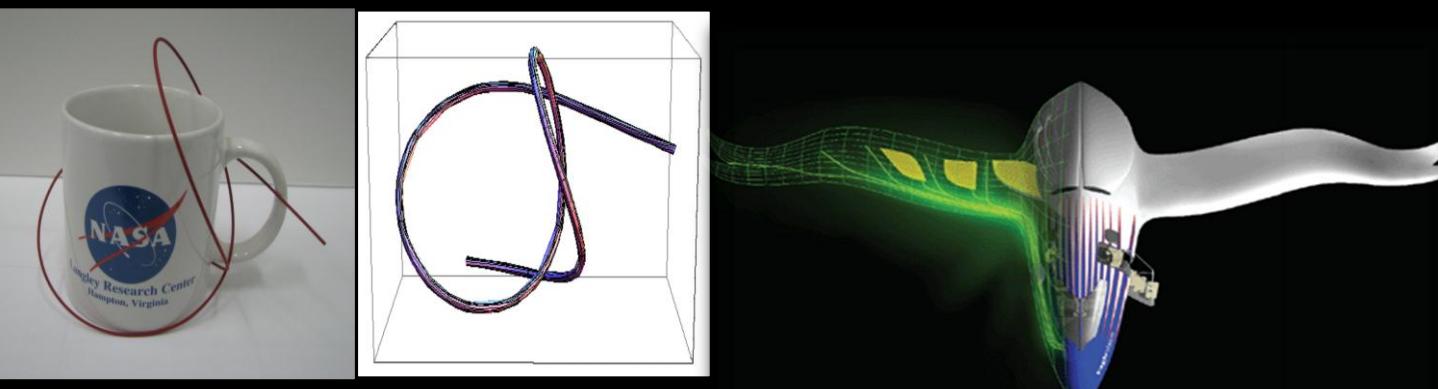
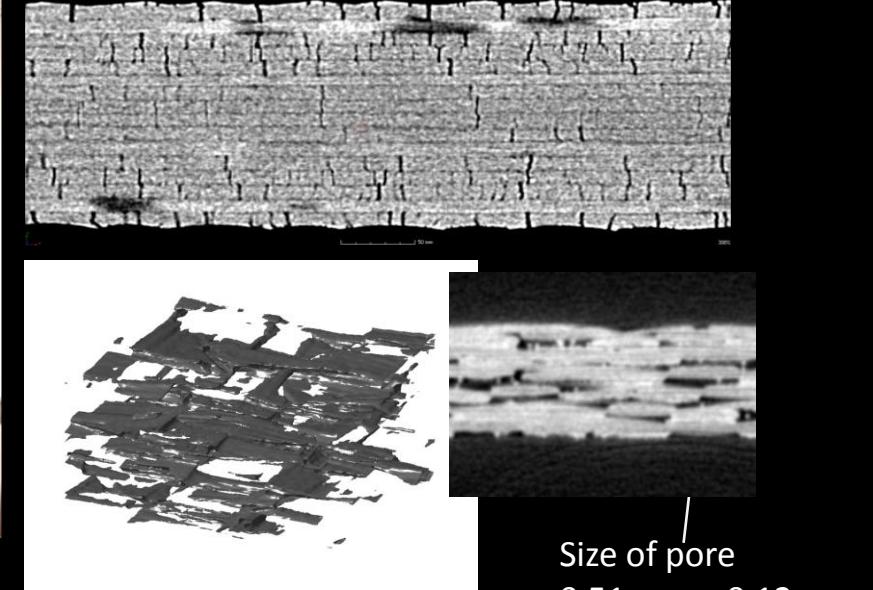
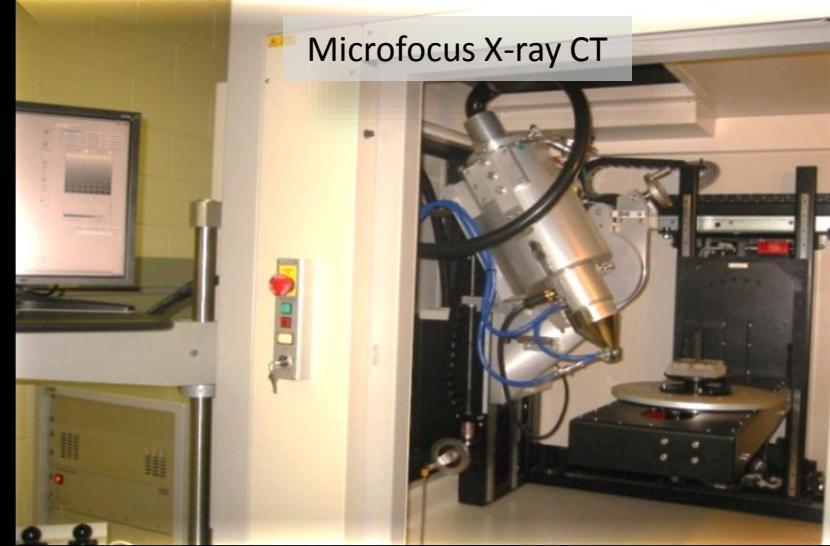
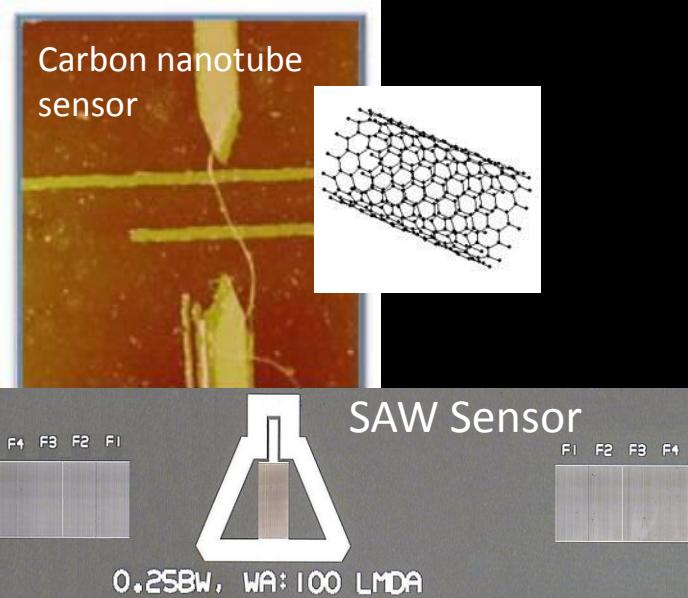


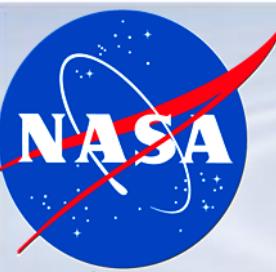
Pulsed THz



Nondestructive Evaluation Sciences Branch

# Many other areas

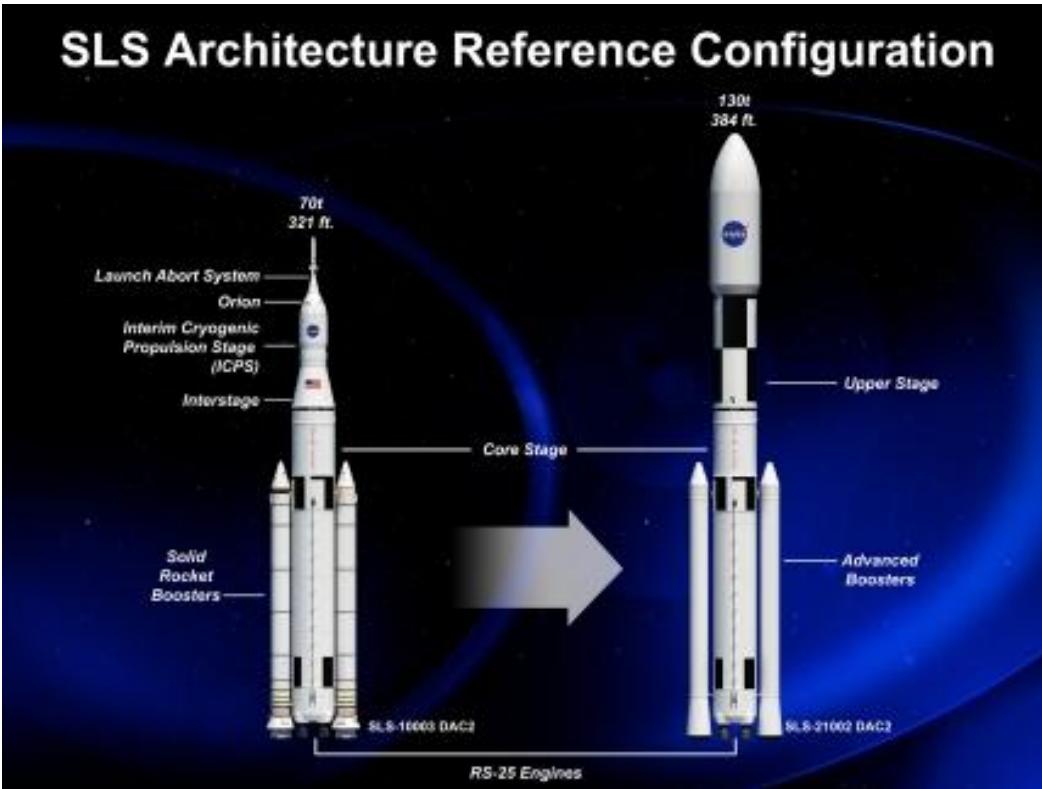


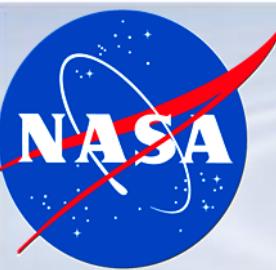


Nondestructive Evaluation Sciences Branch

# Composites in Aerospace

- NASA
- NESB
- Need for composites NDE
- NESB Research
- Conclusion

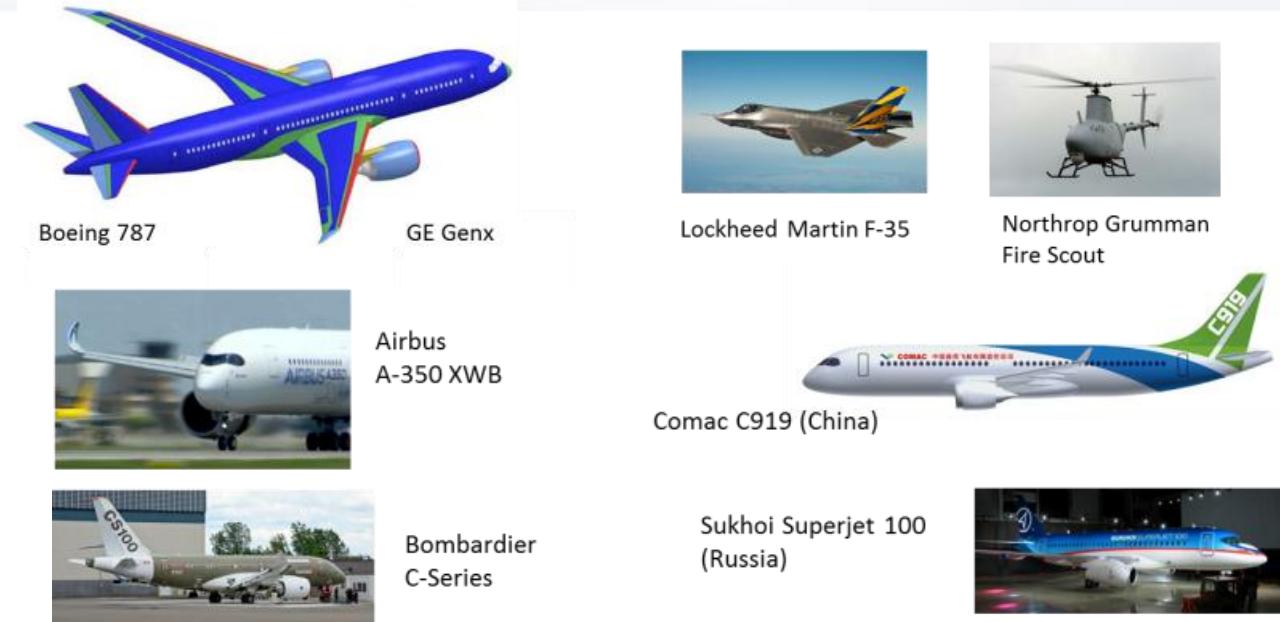


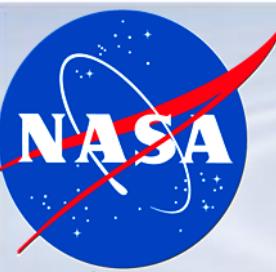


# Advanced Composites Project

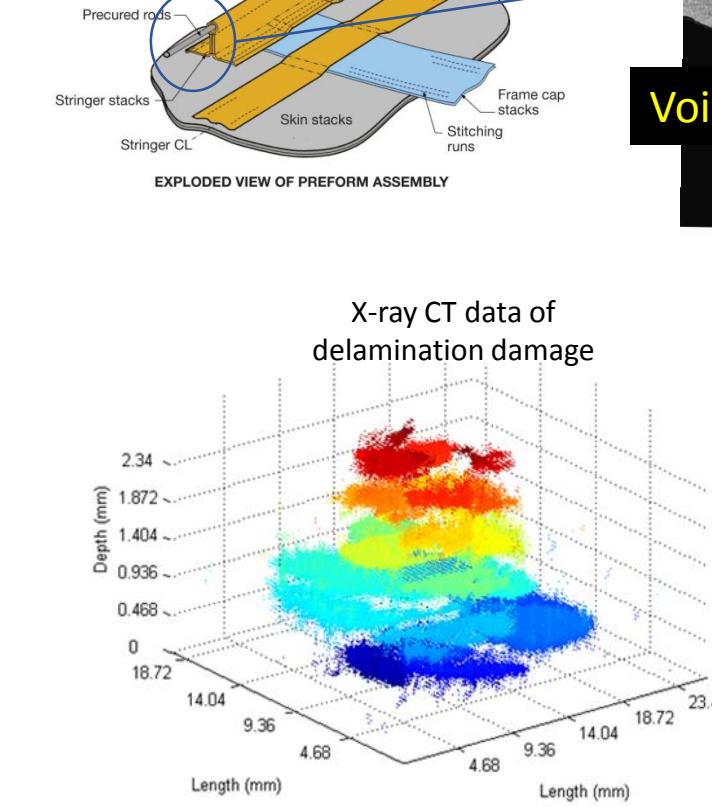
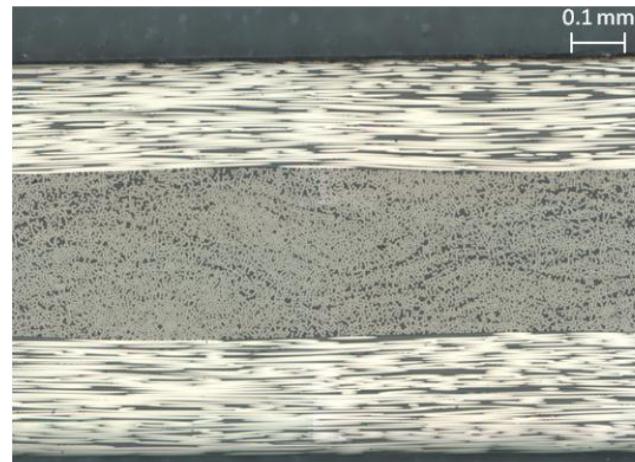
Nondestructive Evaluation Sciences Branch

- 5 Year Project:
  - Reduce timeline for certification of composite structures
    - Currently takes ~20 years from material development to market use
  - Infuse advanced tools to accelerate regulatory acceptance of advanced composites
- Partnership: NASA, FAA, DoD, Industry, University
- NDE of composites will play a key role in all three technical challenge areas:
  1. Predictive capabilities (e.g., damage progression)
  2. **Rapid Inspection**
  3. Enhanced Manufacturing

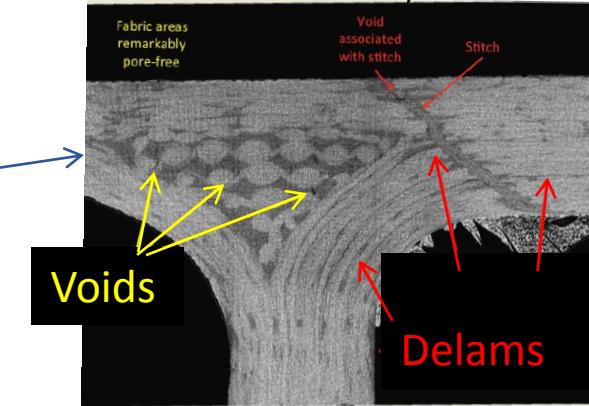




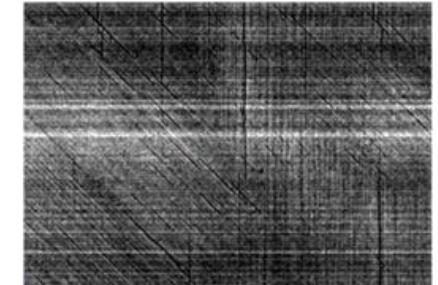
Nondestructive Evaluation Sciences Branch



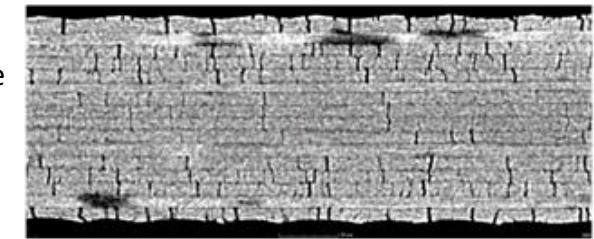
X-ray CT of PRSEUS Joint, From  
NASA TM-2013-217799 by Patrick Johnston



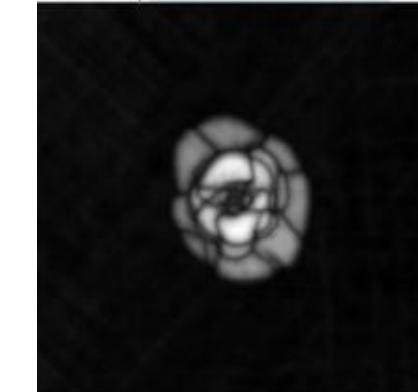
X-ray CT data of  
microcrack damage

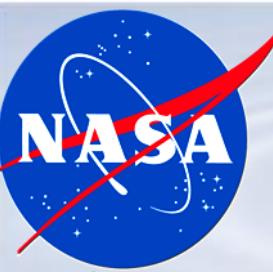


X-ray CT data of  
microcrack damage



UT data of delamination damage



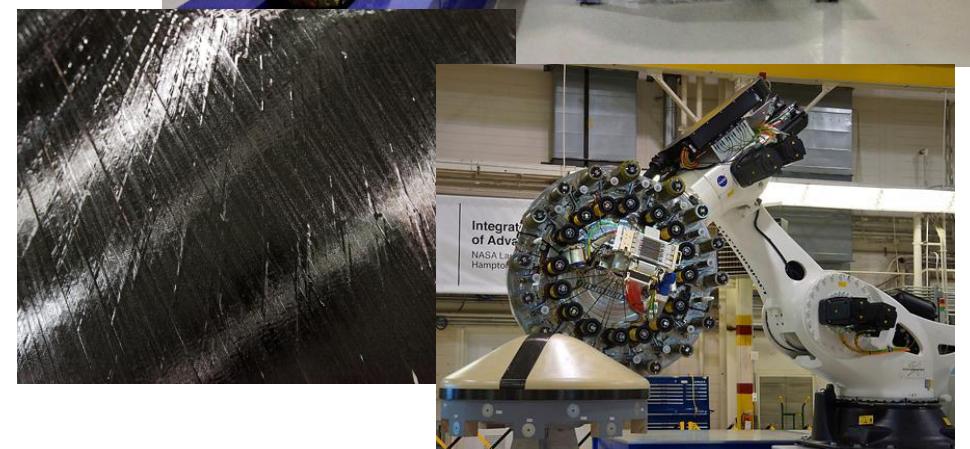


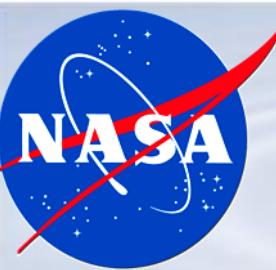
Nondestructive Evaluation Sciences Branch

# NESB Composite NDE Research

- NASA
- NESB
- Need for composites NDE
- **NESB Research**
- Conclusion

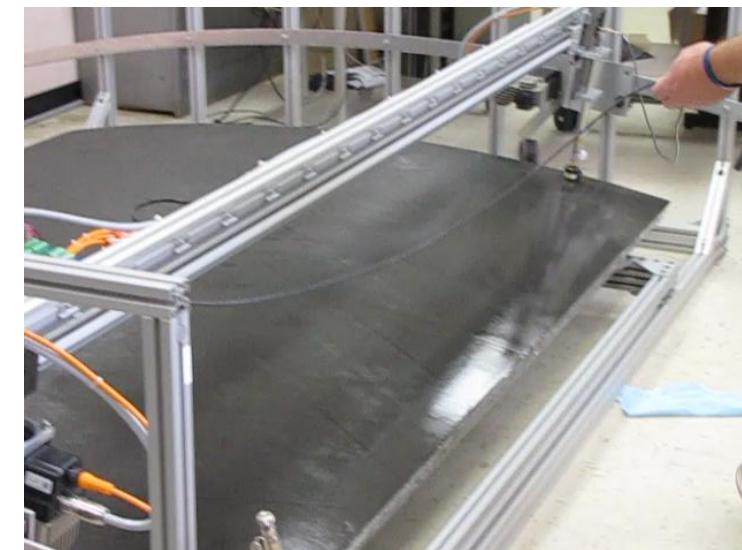
- Focus areas: Inspection of complex geometry components and rapid large area inspection
- Development of new techniques
  - Goal: quantitative damage/material characterization
  - Microcracking, fiber waviness, delamination, porosity
- Validation of detectability
  - Inspectability of complex components
  - Model based validation tools
- Experiment:
  - Thermography, ultrasound, nonlinear ultrasound
- Simulation:
  - Custom code, 3D simulation

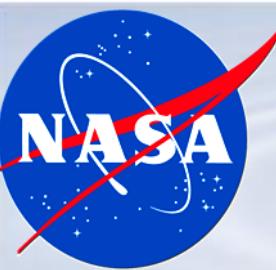




# Large Area Inspection

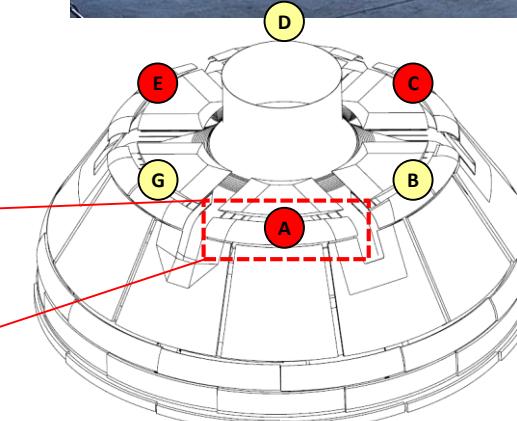
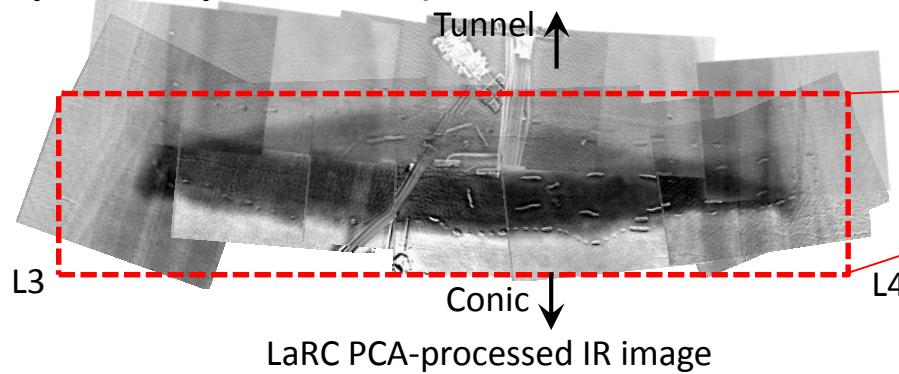
- Flash Thermography
  - Delaminations, disbonding, porosity, skin-to-core disbonding
  - Good for solid laminates and for honeycomb
  - Fast –  $0.09 \text{ m}^2$  (140 in.<sup>2</sup>) in 10-15 sec.
  - Can handle complex geometries
- Non-Immersion Single Element UT
  - Delaminations, disbonding, porosity, matrix cracking, core crushing, skin-to-core disbonding
  - Good for solid laminates and for honeycomb
  - Very high spatial resolution ~.01in. (0.25 mm)
  - Very high speed – 10-12 in. / sec.

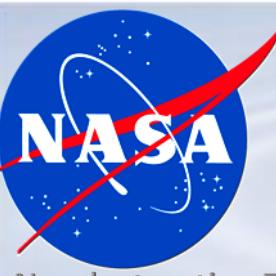




Nondestructive Evaluation Sciences Branch

- Vessel dimensions
  - 3.8m dia. and 3.1m tall
- Full Scale Load testing to failure
- 100% Thermography
- Critical Locations UT
- AE During Loading
- ~ 140 GB of Thermal Data Acquired During Load Testing Cycle (Multiple Inspections)





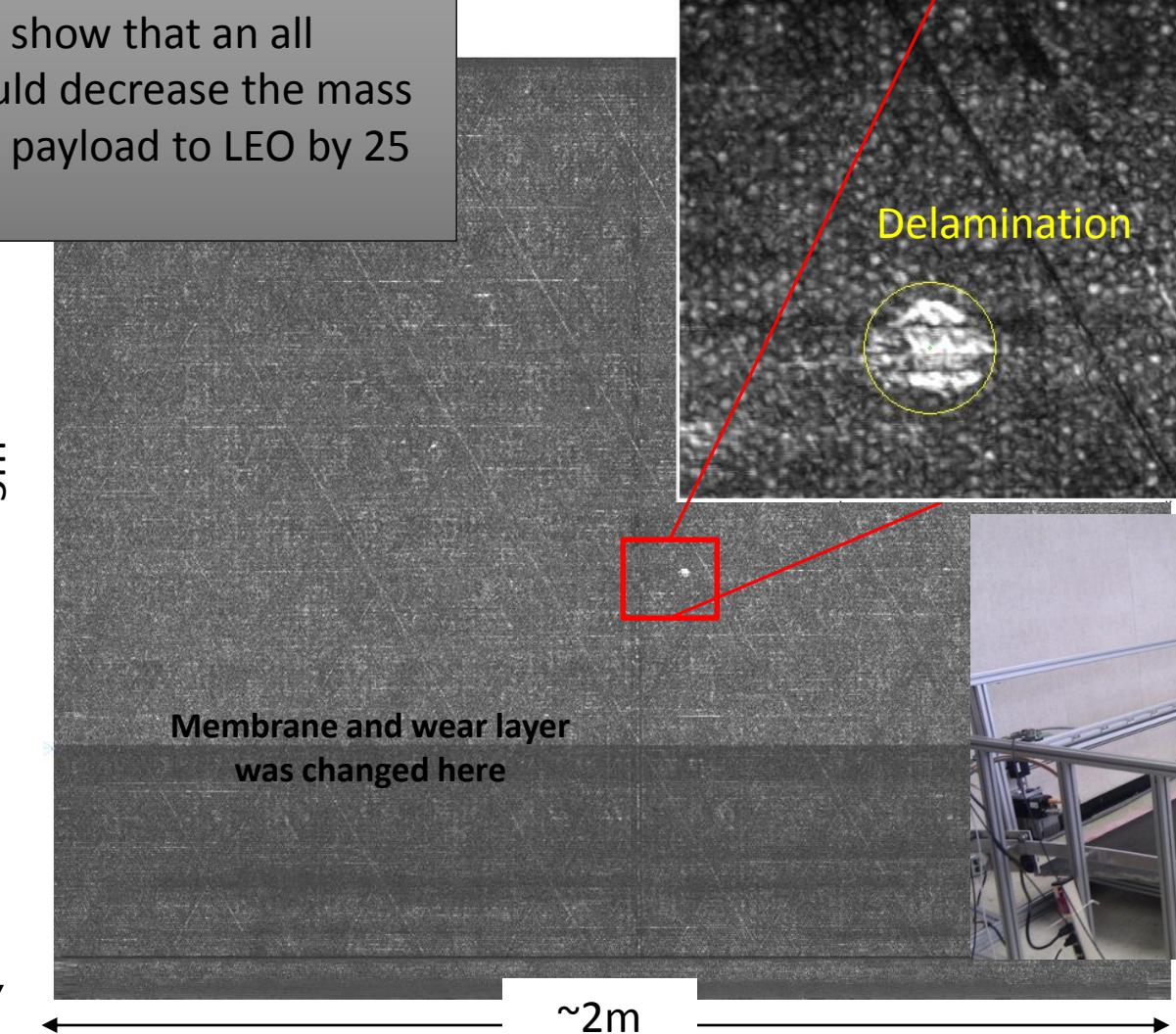
# SLS Composite Payload Fairing

## 1/16 Circumference

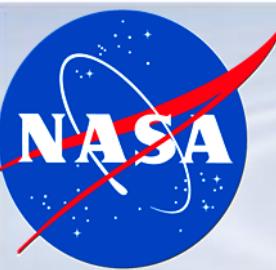


Payload Shroud  
8.4 m Dia.

~3m



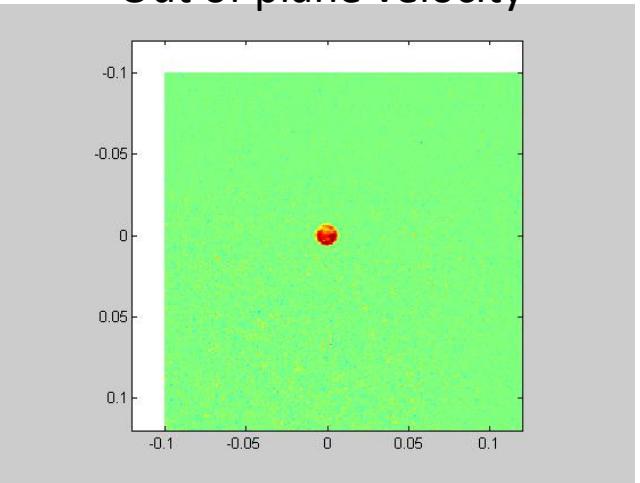
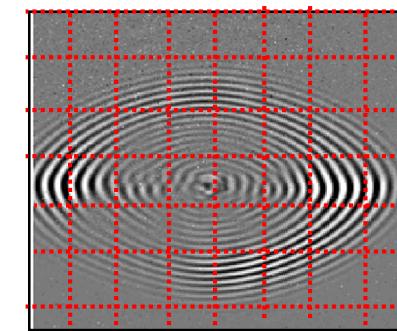
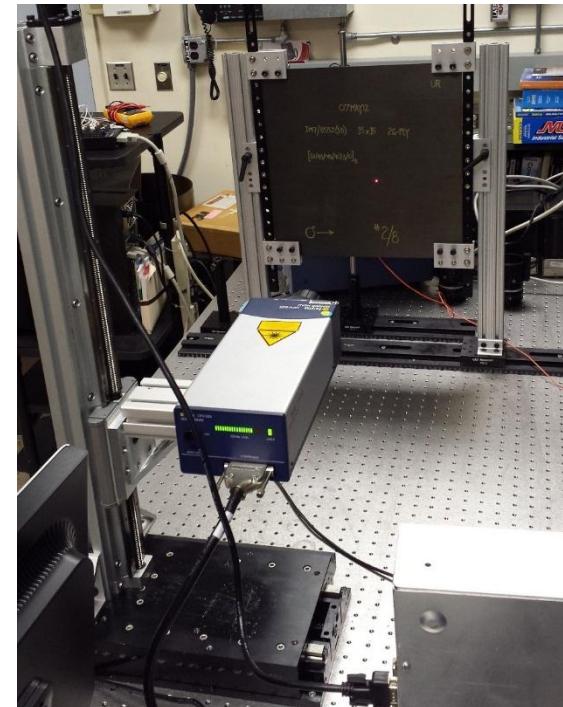
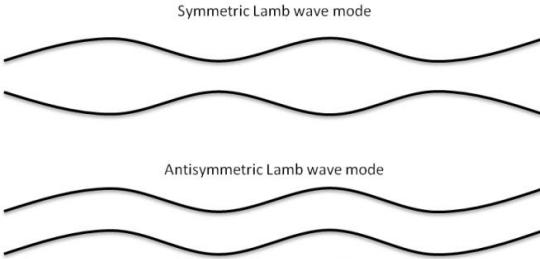
\*Up to 190 GB  
of ultrasonic  
data per panel

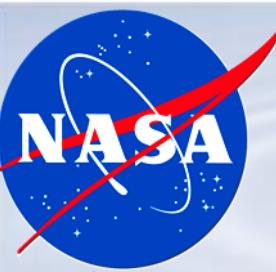


# Guided Wave Ultrasound Research

Nondestructive Evaluation Sciences Branch

- GW created in plate-like specimens due to boundaries
  - Interaction of coupled L and SV with boundaries leads to various modes
- Promise for covering large areas via long distance travel
- Noncontact measurement with Laser Doppler Vibrometry

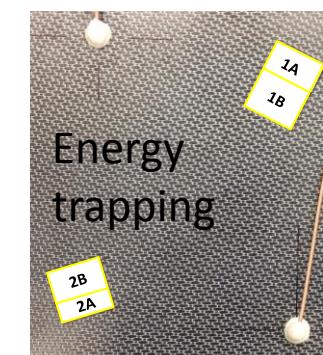
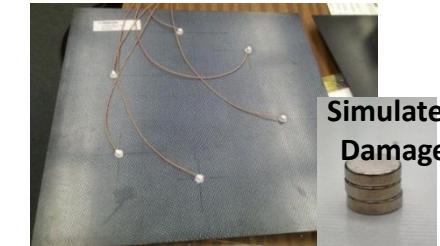
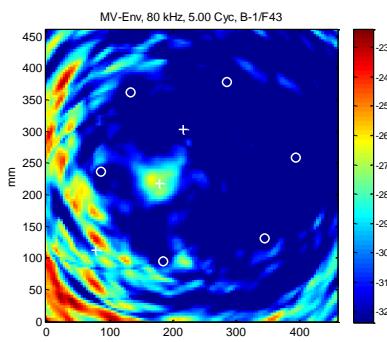
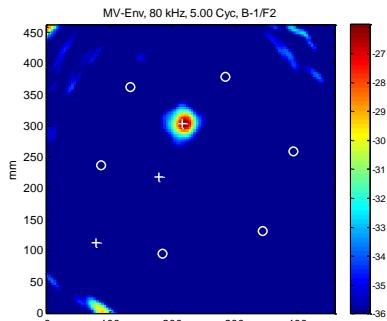




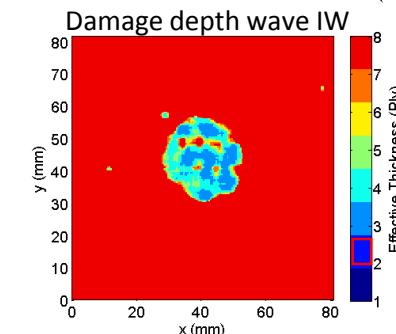
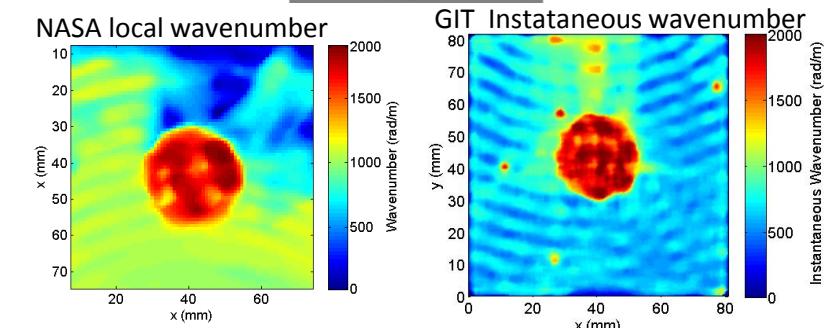
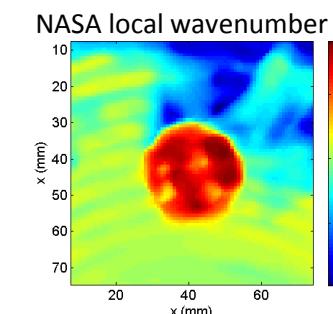
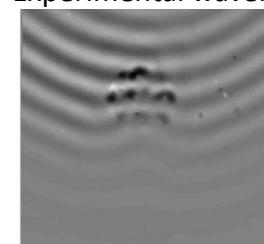
# Wavefield Analysis

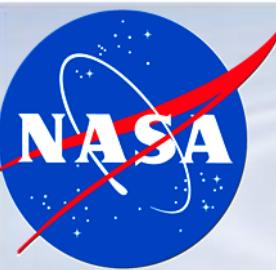
Nondestructive Evaluation Sciences Branch

- NASA/Georgia Institute of Technology NRA starting 01/2013
  - Hybrid SHM/NDE topic: SGWA and AWI to locate *and characterize* damage
- Simulation work led to understanding of energy trapping effect on SGWA
- Moving on to test methods in complex composite components



GIT Experimental wavefield data

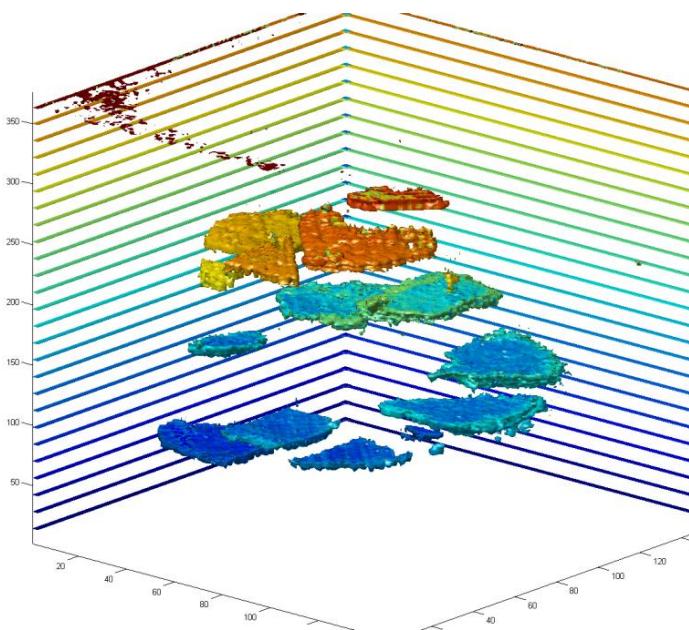




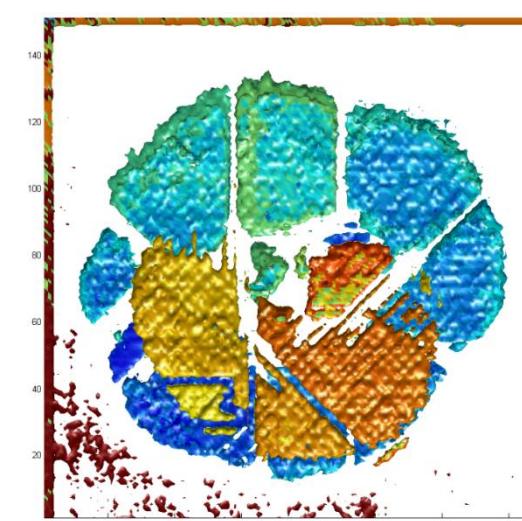
# Wavenumber Analysis

Nondestructive Evaluation Sciences Branch

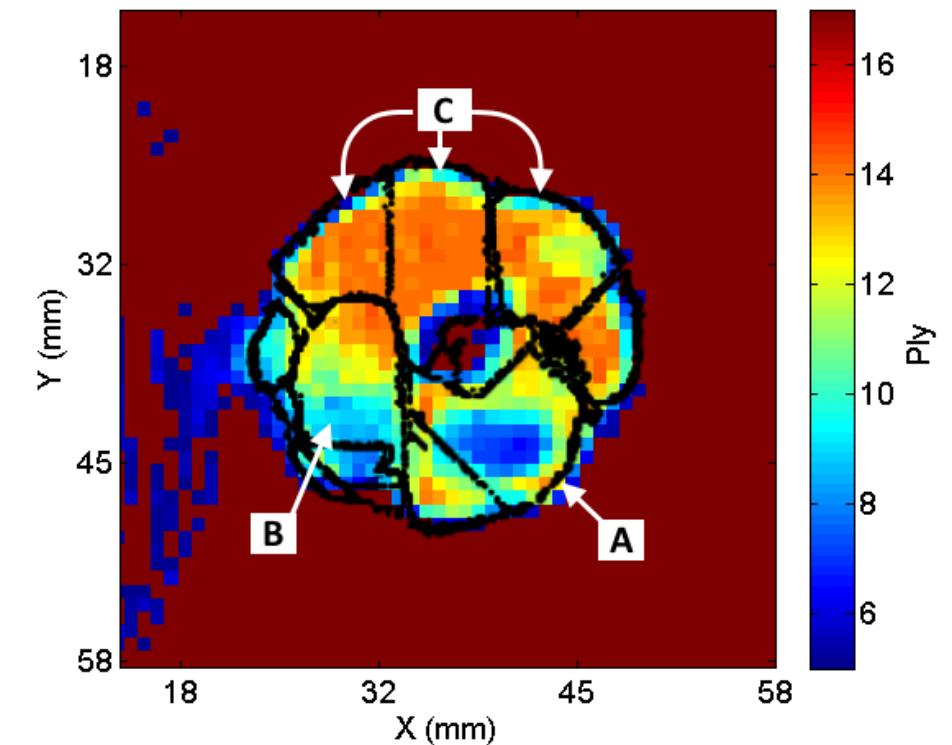
Immersion Ultrasound



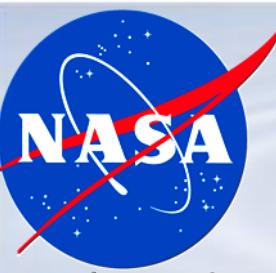
Immersion Ultrasound



Noncontact LDV Wavenumber Analysis



<sup>1</sup> Juarez, P. and Leckey, C. "Multi-frequency Local Wavenumber Analysis and Ply Correlation of Delamination Damage". *Submitted to Ultrasonics*

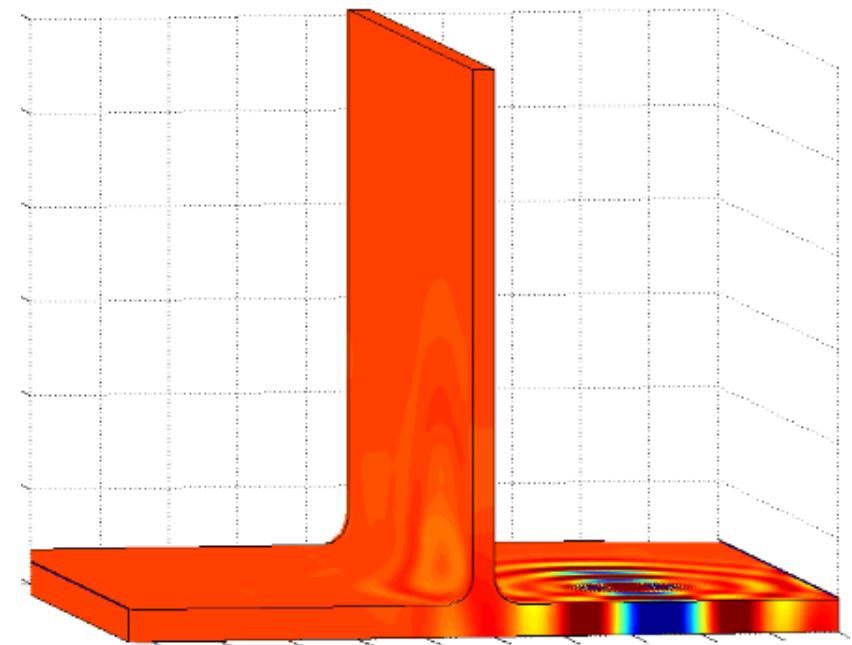


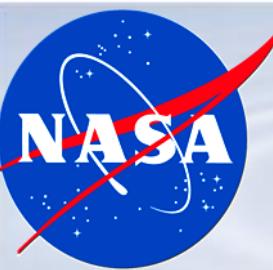
Nondestructive Evaluation Sciences Branch

# NDE/SHM Simulation

- NASA
- NESB
- NDE for Composites
- **NDE Simulation**
- Conclusion

- Simulation of energy interaction with material/structure and damage
  - **Composite focus**
- Realistic NDE simulation tools for aerospace materials enables inspection prediction
  - Establish confidence in ability to inspect: complex components, 'hard to reach' locations, cover large areas, advanced materials (composites)
- Creates cost-effective tools for developing and optimizing *damage characterization* techniques
- Aid in understanding of experimental results
- Simulations enable cost-effective SHM validation

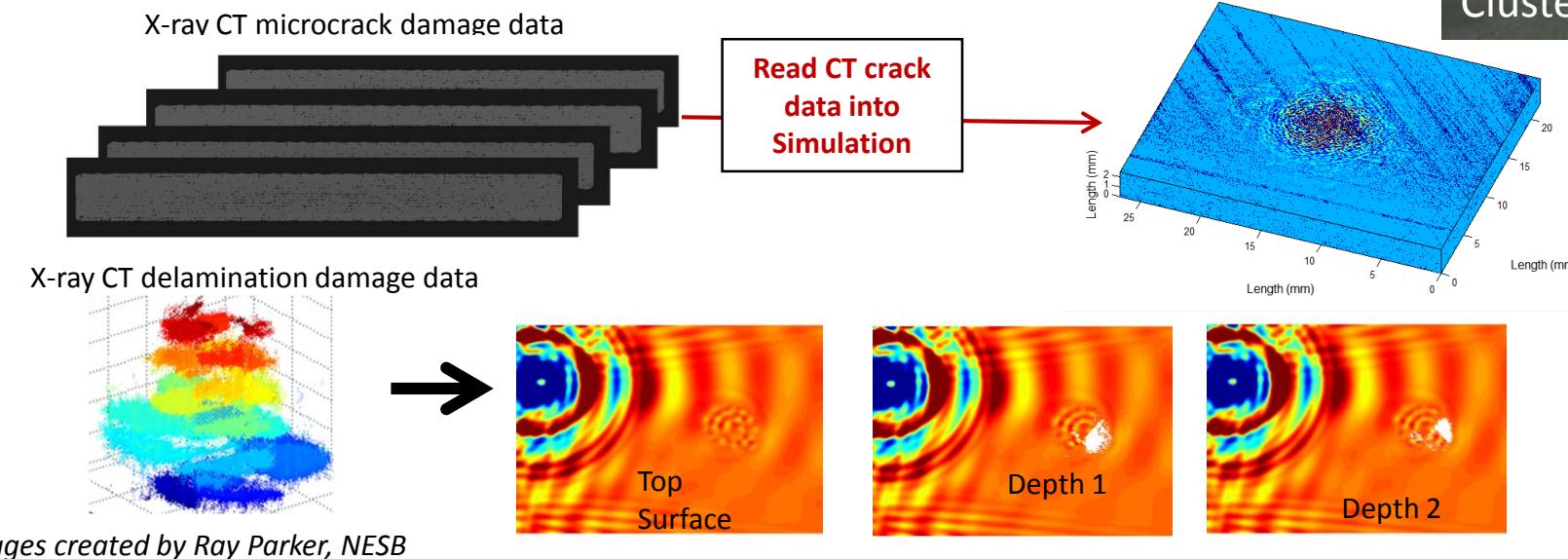




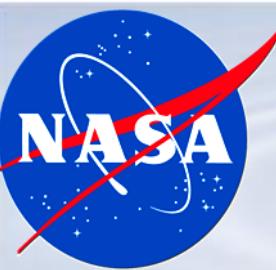
# NESB Custom Simulation Code

Nondestructive Evaluation Sciences Branch

- Custom code simulates 3D wave interaction with *realistic* damage
- Custom EFIT code has many benefits:
  - Speed, memory efficiency, control, adaptability
  - Currently runs on multi-core and cluster computers
  - **Validated against experiment and theory**



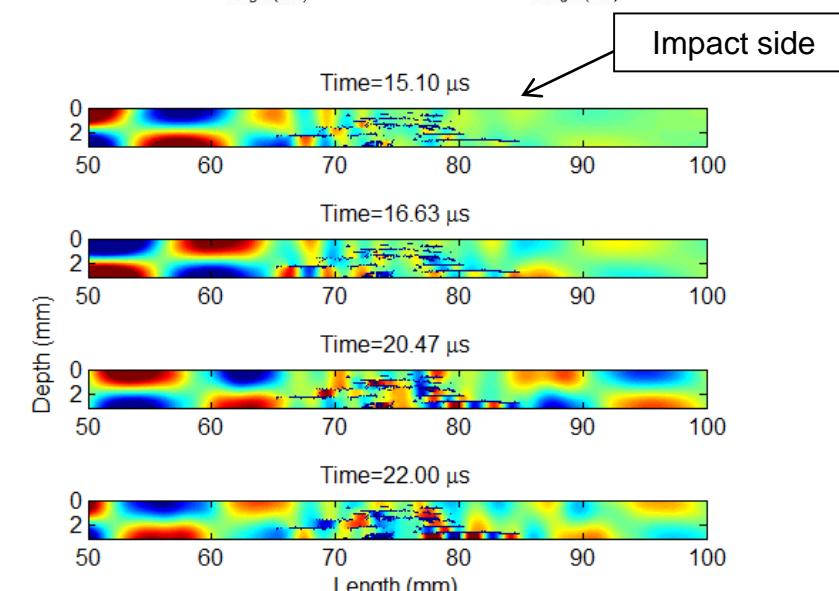
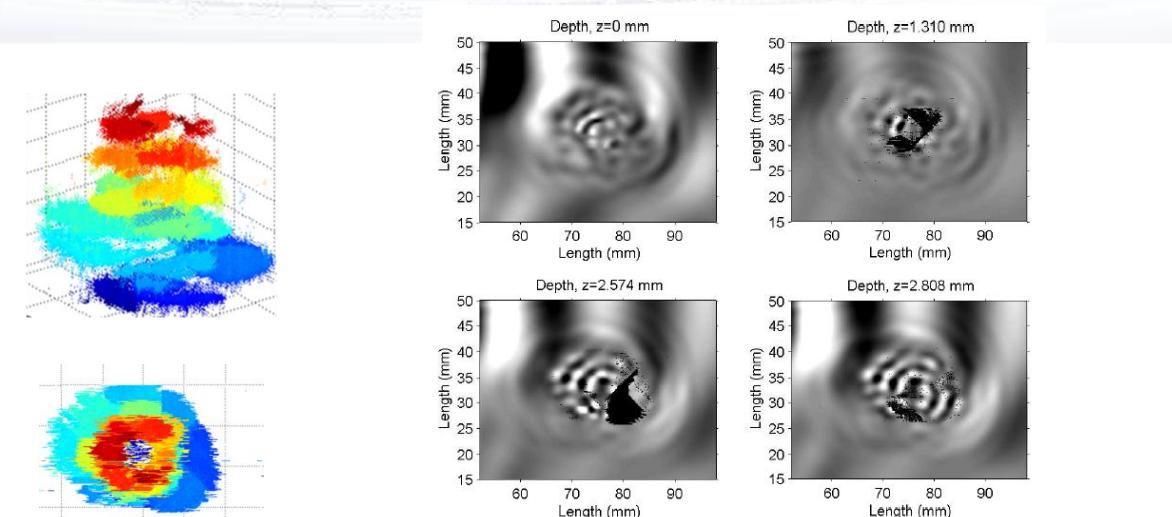
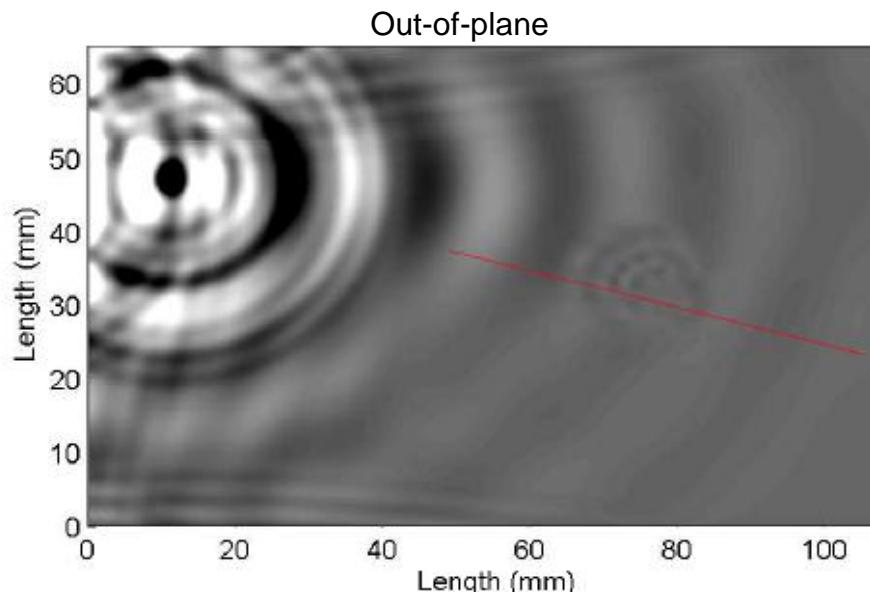
Leckey, Cara AC, Rogge, Matthew and Parker, F. Raymond. "Guided waves in anisotropic and quasi-isotropic aerospace composites: Three-dimensional simulation and experiment." *Ultrasonics* 54.1 (2014): 385-394.

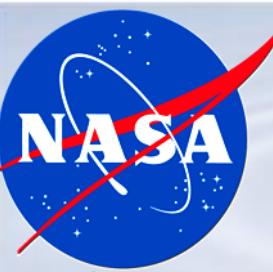


# Guided Wave Example

Nondestructive Evaluation Sciences Branch

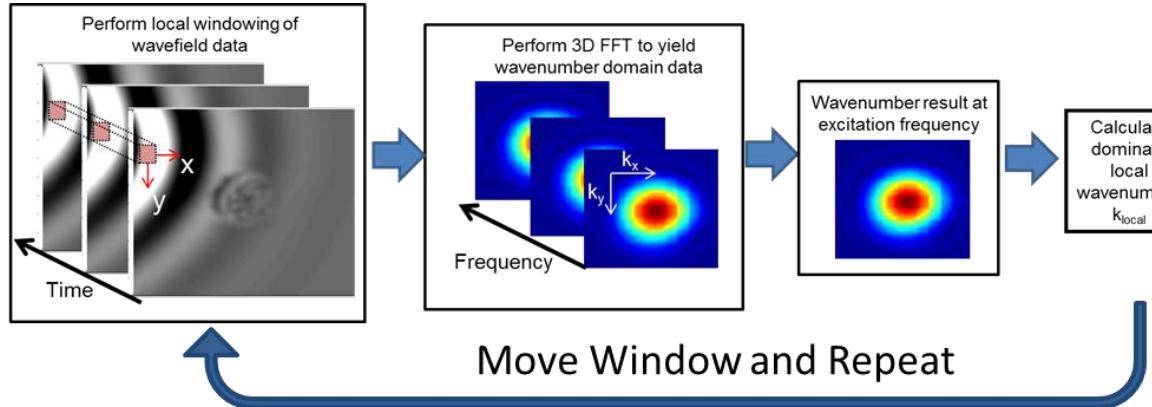
- 3D EFIT: 1.8 billion grid cells
  - 110 mm x 65 mm x 3.2 mm
- Run on 80 core 1TB shared memory machine
- Step size=23.4 $\mu$ m,  $\lambda_{\min}/64$
- Images show shorter wavelength scattering from damage





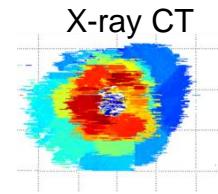
# Data Processing: Wavenumber Analysis

Nondestructive Evaluation Sciences Branch

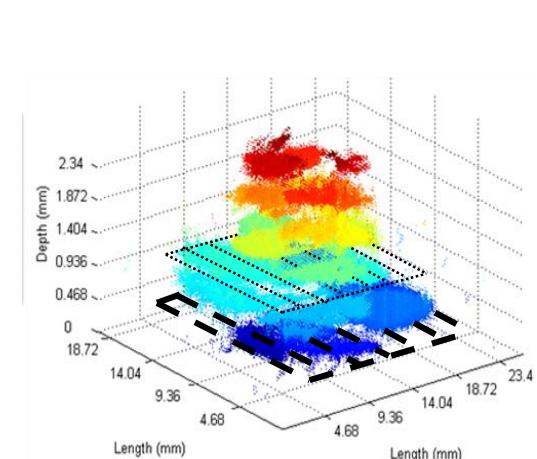


Local Wavenumber Analysis Technique:

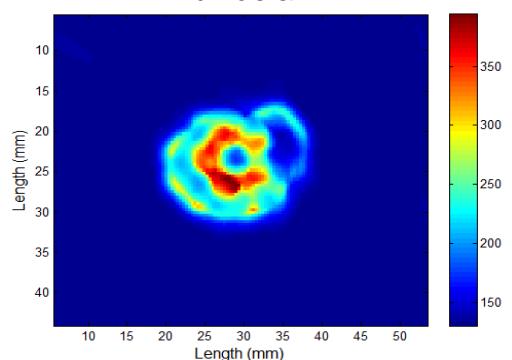
- 1) 3D FT of Hann windowed wavefield, local window
- 2) Select 3D FT slice at excitation center frequency
- 3) Calculate dominant wavenumber of local window



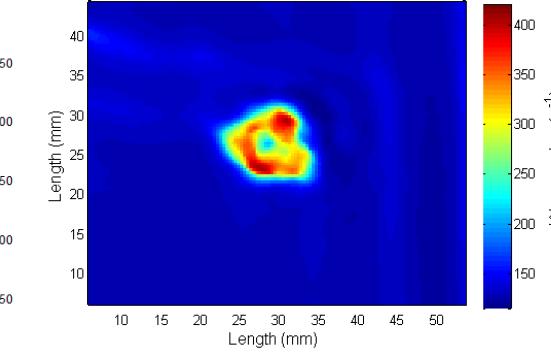
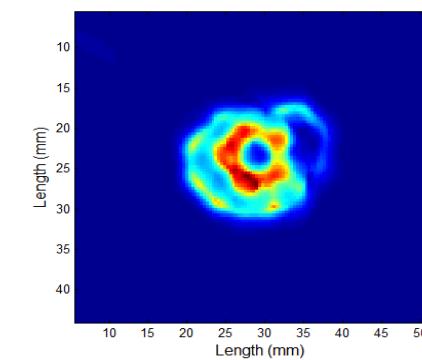
Case 3,  
Half delam removed



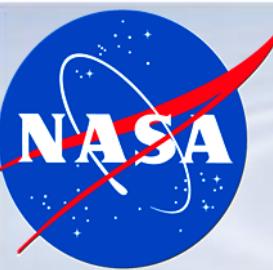
Case 1  
Full delam



Case 2,  
Hidden delam removed



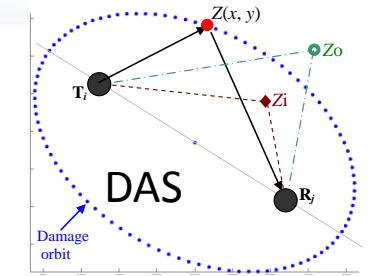
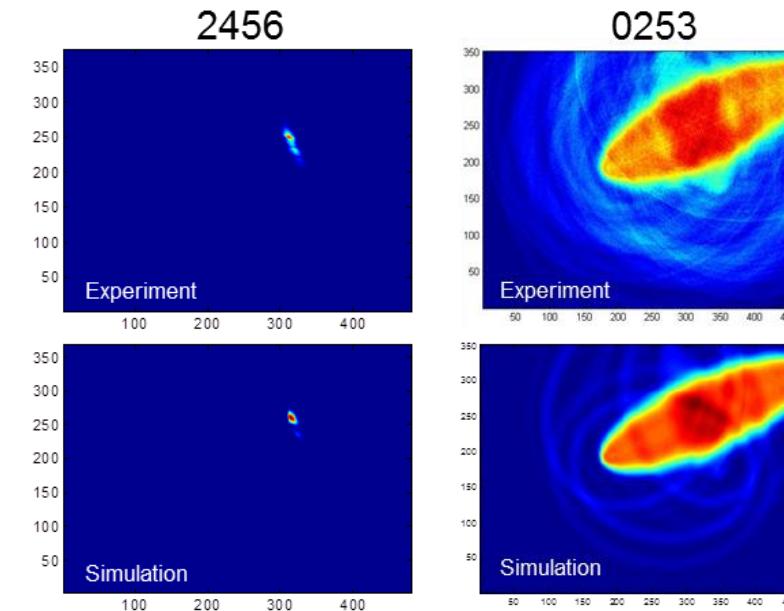
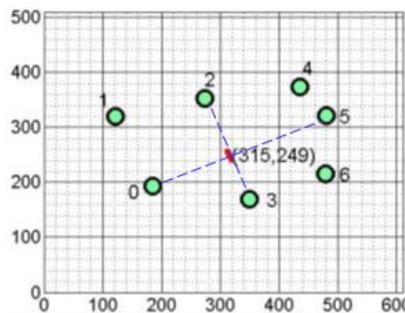
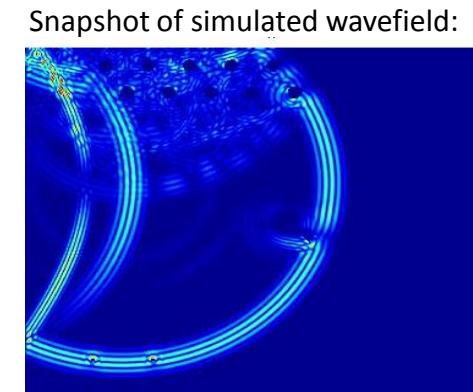
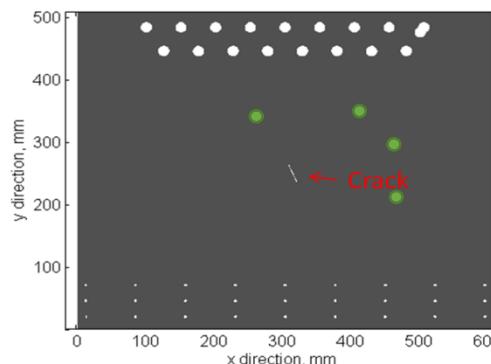
Rogge, M. and Leckey, C.; "Characterization of impact damage in composite laminates using guided wavefield imaging and local wavenumber domain analysis"; *Ultrasonics*, Vol 53, pp 1217-1226 (2013)



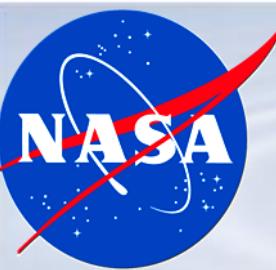
# Model Based Detectability Studies

Nondestructive Evaluation Sciences Branch

- NASA/University of South Carolina\*
- Started with simple isotropic (aluminum) case
- Results<sup>1</sup> demonstrated use of 3D simulation data in place of experimental data for investigating sensor location w.r.t. damage



<sup>1</sup>Yu, L. and Leckey, C. "Lamb Wave Based Quantitative Crack Detection using a Focusing Array Algorithm". *Journal of Intelligent Material Systems and Structures*, Vol 24, pp 1138-1152 (2013)



# Conclusion

- NASA needs quantitative NDE for aerospace components, including:
  - Rapid inspection for large scale parts
  - Techniques for complex geometry composites
  - Validation methodologies for determining inspectability
- Experiment and simulation are needed to develop optimized, validated inspection/monitoring techniques
- NESB is performing ongoing research in these areas

**A list of related publications can be found at:**

<http://nde.larc.nasa.gov/physicsbased.shtml>

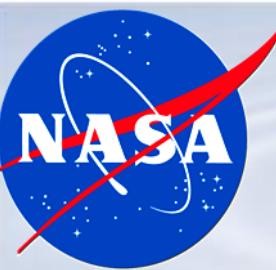
Thanks to:

- Peter Juarez
- Jeffrey Seebo

## QUESTIONS?

\*NASA/USC work under SAA1181

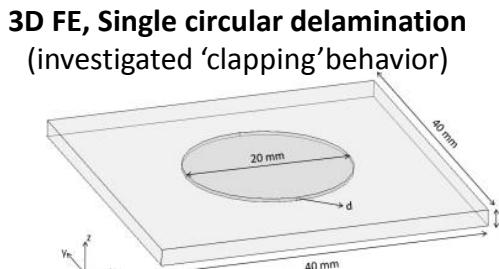
\*\*NASA/GaTech work under NRA NNX12AL13A



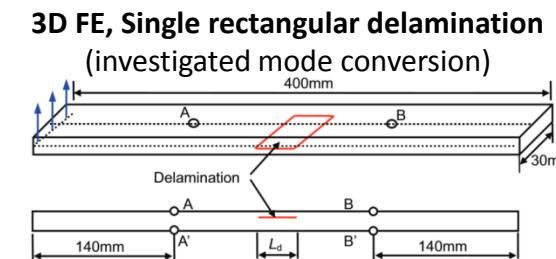
# Simulation SOA and Gaps

Nondestructive Evaluation Sciences Branch

- SOA of NDE and SHM modeling/simulation *not adequate* for future needs, including:
  - Larger scale simulations
  - Composites
  - Advanced designs
  - Realistic damage scenarios

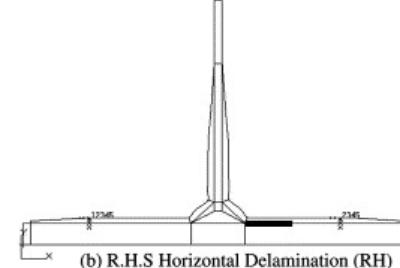


From: Delrue, Steven, and Koen Van Den Abeele. "Three-dimensional finite element simulation of closed delaminations in composite materials." *Ultrasonics* 52, pp 315-324 (2012)



From: Liu, Zenghua, et al. "Delamination detection in composite beams using pure Lamb mode generated by air-coupled ultrasonic transducer." *Journal of Intelligent Material Systems and Structures*: 1045389X13493339. (2013)

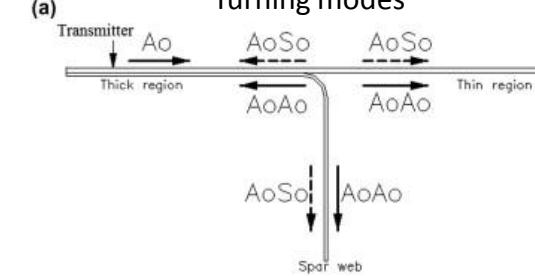
## 2D FE, Single 'strip' delamination



Kesavan, A., et al. "Damage detection in T-joint composite structures." *Composite Structures* 75.1 : 313-320. (2006)

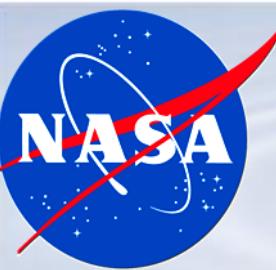
## 2D FE (ANSYS)

### Turning modes



Ramadas, C., et al. "Interaction of Lamb mode with structural discontinuity and generation of "Turning modes" in a T-joint." *Ultrasonics* 51.5: 586-595.

(2011)



Nondestructive Evaluation Sciences Branch

# Computational Trends

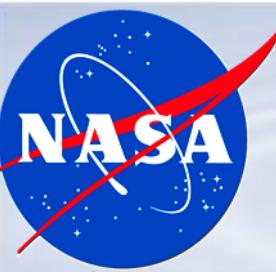
- Computational power per unit space increasing, cost decreasing
- iPad2 has as much processing power as Cray 2 (world's fastest computer in mid 1980s)
- Cost per GFLOP (adj for inflation)
  - 1984: \$42M
  - 1997: \$42k
  - 2007: \$52
  - 2013: \$0.12
- Simulations will play an increasing role in the future science and engineering (including NDE)



Cray 2 Supercomputer  
NASA Langley Research Center

3/23/1989

Image # EL-2001-00428



# Guided Wave Simulation

